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## Coping with a big nuclear accident

Society's extensive figurative vocabulary of nuclear terms demonstrates just how far atomic energy has permeated the public's consciousness and imagination, in a way matched by few other scientific discoveries. Hence we can understand perfectly well a news report saying that the stock market has had a "meltdown" and we grasp immediately that the political "fallout" could be significant if the number of firms affected has reached a "critical mass". But how do we cope when an actual nuclear reactor melts down and deposits a significant amount of radioactive fallout over the surrounding area? Exactly this happened at Chernobyl in April 1986, where to make matters worse, the reactor went super prompt critical for a few seconds[1], depositing a large amount of additional heat into the core. A quarter of a century later, another very large radioactive release occurred at the Fukushima Daiichi nuclear power station. Here the operating reactors were shut down as soon as the Tohoku Earthquake was detected but the tsunami following on close behind knocked out the reactor cooling system. The overheated fuel assemblies then reacted with steam to produce hydrogen gas, which led to explosions in the reactor buildings and the release of radionuclides into the environment.

In both cases, the authorities' principal response for protecting the public was to move large numbers of people away from the surrounding area. A total of 335,000 were relocated after Chernobyl, never to return. Meanwhile after the accident at Fukushima Daiichi, 111,000 people were required to leave areas declared as restricted and an additional 49,000 joined the exodus voluntarily; about 85,000 had not returned to their homes by 2015. Were these sensible policy reactions? Was there an alternative? How should we respond to a big nuclear accident in the future? These were the questions behind the multi-university NREFS research study – Management of Risk Issues: Environmental, Financial and Safety – carried out for the Engineering and Physical Sciences Research Council as part of the UK-India Civil Nuclear Power Collaboration (NREFS, 2015). This Special Issue carries the 10 closing papers from that project.

The NREFS approach is predominantly quantitative, and Thomas (2017a) outlines the methods used and the results obtained, and recommends such mathematically based methods as aids to penetrating the fog of uncertainty and confusion following a major nuclear accident. They should, Thomas suggests, provide the basis for making decisions that will do more good than harm. He calls for the demystification of nuclear accidents and specifically for decision makers to be aware in advance that they should not adopt blindly the strategies used to manage past severe nuclear accidents. Using available data on the health consequences of the two severe nuclear events discussed above, the NREFS project has shown these strategies to be excessive in view of the actual, as opposed to feared, level of radiological risk faced by the public.

Waddington et al. (2017a) find that the numbers relocated after both the Chernobyl and Fukushima Daiichi accidents were very much too high. (They use the term

[1] Super prompt critical means that the reaction was sustained and could grow using prompt neutrons only. The increased fission rate could be maintained for only a few seconds, however, before the high temperature induced in the core caused its reactivity to drop and the reaction to shut down automatically (the Nordheim-Fuchs effect). The disrupted core then stayed subcritical and shut down.

"relocation" to imply that the people concerned will live away from a designated exclusion zone for a substantial period of time, after which return to the original location starts to become problematical.) Based on the Judgement- or J-value method, between 5 and 10 times too many people were moved away from the Chernobyl area between 1986 and 1990, and the authors find it difficult to justify moving anyone away from Fukushima Daiichi on grounds of radiological protection. The analysis is retrospective, and so blame is not apportioned to the authorities concerned. However, the authors suggest that it should be taken into account in future decision making. They go further and suggest that more comprehensive radiological data collection could be fed 'on the fly' into the analysis during an accident to assess the potential effectiveness of candidate decisions. Some thought-provoking comparative statistics on life expectancy are also provided between the Chernobyl region after the world's worst nuclear accident and the UK in the 21st century. The authors suggest that the 900 people most under threat from radiation if they had not moved out in the 2nd relocation from Chernobyl in 1990 would have lost just 3 months' life expectancy if they had stayed in situ. Meanwhile the 6,800 people who faced the highest radiation dose, had they not been moved out in the 1st Chernobyl evacuation of 1986, would have lost 3 years or more of life expectancy, with 5.6 years constituting the average reduction. These numbers are then compared with

- the 4½ months life expectancy lost by the average Londoner to air pollution;
- the 3¼ years difference in life expectancy between the average person living in Harrow, North London and his/her counterpart in Manchester; and
- the 8.6 years of life that baby boys born in Blackpool lose compared with those born in London's Kensington and Chelsea.

The J-value is a new approach (validated for 90% of the world's nations during the course of the NREFS study) that balances safety spending against the extension of life expectancy it brings about. It improves on currently used methods by introducing greater objectivity as a result of its incorporation of the life-quality index (Nathwani and Lind, 1997) at its core. This allows the monetisation of future years of life using GDP per head plus an appropriate value of risk-aversion (Thomas, 2016, gives a discussion of risk-aversion and its development as an economic parameter over the past 300 years). The J-value is found by dividing the actual cost of the safety measure by the maximum that can be spent before life quality declines, implying that the expenditure is justified when J is less than 1.0. The J-value possesses the considerable advantage in the nuclear context that, unlike other approaches, it allows loss of life both in the short and in the long term (as a result of radiation exposure, for example) to be measured on the same scale.

The broad thrust of the J-value findings is backed up by two other NREFS studies that employed different and diverse assessment methods. Yumashev et al. (2017) apply Bellman's principle of optimality to determine the best decisions to be taken after a large range of big nuclear accidents. They find relocation not to be a sensible policy measure in any of the hundreds of base case scenarios they examined; it is rarely optimal in any of their sensitivity cases. See also Yumashev and Johnson (2017). Meanwhile, after carrying out a review of current UK planning for a big nuclear accident (Ashley et al., 2017a), Ashley et al. (2017b) examine, using Public Health England's PACE-COCO2 program suite, the likely effects on the public of a severe accident on a fictional nuclear reactor located on the South Downs of England. Even after applying a rather strict safe-return criterion, they find that the expected number of people needing to be relocated is only 620, orders of magnitude below the figures for Chernobyl and Fukushima Daiichi.

By contrast with relocation, the J-value method provides strong support for remediation after a big nuclear accident (Waddington et al., 2017b). Similarly, remediation and temporary food bans are quite likely to be components of an optimal economic strategy (Yumashev et. al., 2017). Meanwhile PACE-COCO2 (Ashley et al., 2017b) quantifies the expected cost of lost agricultural production as £130M, within an overall total expected accident cost of £800M (excluding reactor damage and lost electricity sales).

Waddington et al. (2017c) also use the J-value to examine the UK's response to Chernobyl of imposing restrictions on lamb produced on hill pastures in Cumbria, Wales, Scotland and Northern Ireland. The study endorses the Government's decision to remove the controls in 2012, but finds that the positive effect of the curbs had fallen to such a low level (equivalent to increasing the life expectancy of UK consumers by 8 seconds) by the time they were dropped as to call into question why the restrictions were not taken away much earlier.

The caution displayed on hill sheep controls finds an echo in the approach of those regulating nuclear energy in the UK. Nuttall et al. (2017) report on a structured discussion involving a panel of experts drawn from risk specialists, insurance specialists, lawyers concerned with nuclear law, and, in addition, safety and environmental regulators. The authors contrast the "stoicism" of those closest to implementing policies and procedures to counter nuclear risks with the greater sense of uncertainty evident amongst those charged with regulating nuclear energy.

While the loss of life expectancy for an exposed population may be rather small after a big nuclear accident, as noted above, what about those people, fortunately few in number, who actually contract a fatal, radiation-induced cancer? How much life will they lose? These are the questions addressed in Thomas (2017b). Based on the model for mortality period devised by Lord Marshall of Goring in the 1980s and the linear, no-threshold model for radiation risk endorsed by the International Committee for Radiological Protection (ICRP), he finds that the average radiation cancer victim will live into his/her 7$^{th}$ or 8$^{th}$ decade and lose between 8 and 22 years of life expectancy. This implies that, on average, a UK citizen has twice as much or more to lose from being killed outright in a road or rail accident as opposed to dying as result of a radiation cancer induced at the same moment. The author draws attention to the limitation this finding exposes in the thinking behind the one-size-fits-all "value of a prevented fatality" (VPF), currently used widely in the UK for cost-benefit analysis.

The final paper (Thomas and Waddington, 2017) provides validation for the J-value method by using it to give the first theoretical explanation of the regular shape found in the Preston curve, which charts life expectancy at birth against GDP per head for all the nations of the world. The paper also proposes the life expectancy ratio (population-average life expectancy divided by life expectancy at birth) as a measure of national development, predicting and then corroborating that its starting value for a very poor county will be ⅔, but that this figure will decrease towards ½ as the country progresses from undeveloped to highly developed. The authors have also provided the first objective estimation of an important economic variable, the pure time discount rate, used, for example, in Lord Stern's analysis of the economic effects of climate change and, in fact, key to its results.

The results from the NREFS project presented here are based on a diverse set of methods but show a significant scientific and economic convergence on how best to respond to a big nuclear accident. Although it was treated as the prime policy choice at both Chernobyl and Fukushima Daiichi, mass relocation emerges as unlikely to be a good policy option. The NREFS papers indicate that indiscriminate implementation of relocation after a big nuclear accident in the future would very likely transgress the ICRP's fundamental "principle of justification", namely that any measure adopted should do more good than harm.

It is understandable that decision makers react to socio-political pressures but it is very important that decision making takes place against the best available analysis of the impact of the actions to be undertaken, given the very considerable human and monetary consequences that result from over-reaction. Quantitative analyses such as those considered above can provide a "baseline" for the guidance of those who need to judge the best course of action. If a decision is taken that goes further than warranted by the results of the baseline analysis, decision makers should justify why resources are being employed significantly beyond what is cost beneficial.

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